LHC Signals of

MSSM
Electroweak Baryogenesis

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Baryons

- Baryon density of the universe: [WMAP '06]

$$\eta \ = \ \frac{n_B}{n_\gamma} = (6.5 \pm 0.3) \times 10^{-10}.$$

where $n_B = (\#\ baryons) - (\#\ anti{-}baryons)$.

- Only baryons, not anti-baryons.

  $\rightarrow$ Baryon Asymmetry of the Universe (BAU).

- No Standard Model (SM) explanation.

- MSSM $\rightarrow$ Electroweak Baryogenesis

Baryogenesis Mechanisms

Electroweak Baryogenesis (EWBG)

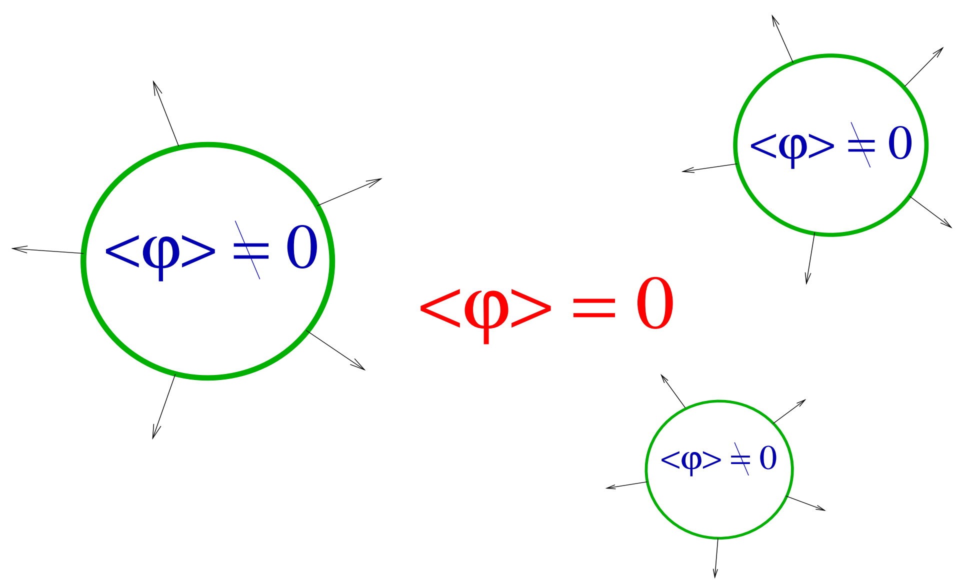
$\rightarrow$ baryon production during the electroweak phase transition.

[Kuzmin,Rubakov,Shaposhnikov '85]

1. Electroweak symmetry breaking as the universe cools.

2. Nucleation of bubbles of broken phase.

3. Baryon production near the expanding bubble walls.



1. The Electroweak Phase Transition

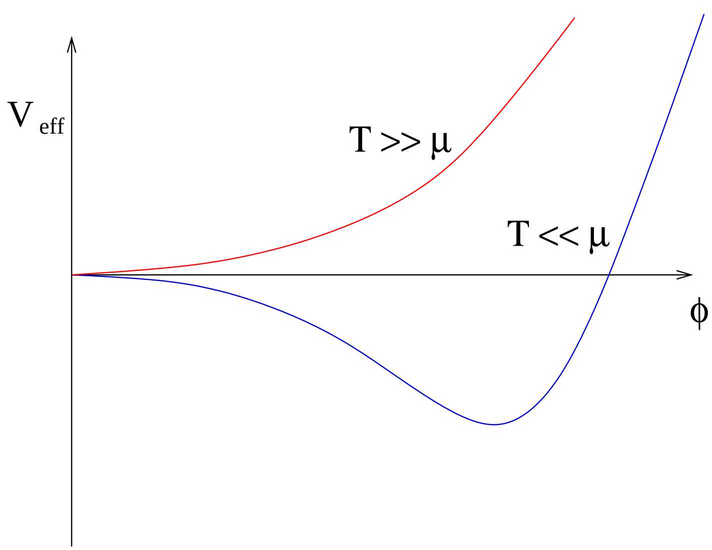
- Order parameter = Higgs VEV $\langle\phi\rangle$:

$$\langle\phi\rangle = 0 \Rightarrow SU(2)_L \times U(1)_Y \text{ is unbroken.}$$

$$\langle\phi\rangle \neq 0 \Rightarrow SU(2)_L \times U(1)_Y \to U(1)_{em}.$$

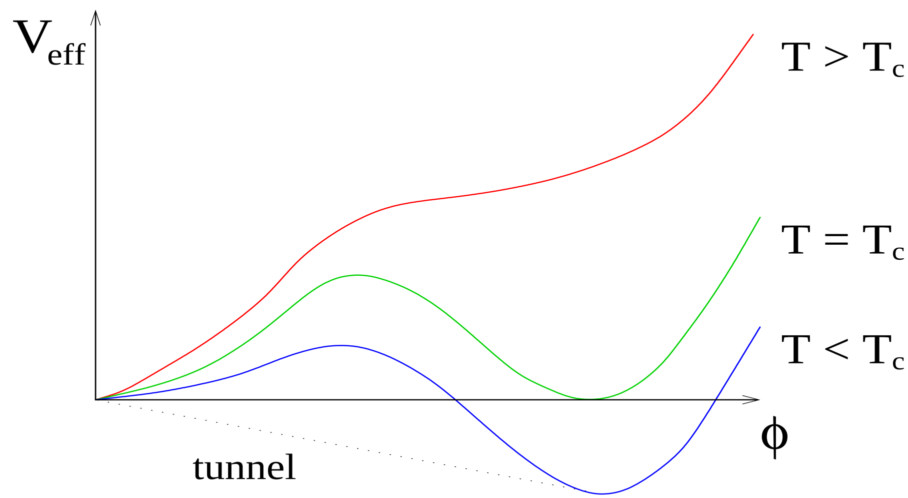
- Effective potential:

$$V_{eff} = (-\mu^2 + \alpha T^2)\phi^2 - \gamma T\phi^3 + \frac{\lambda}{4}\phi^4 + \ldots$$

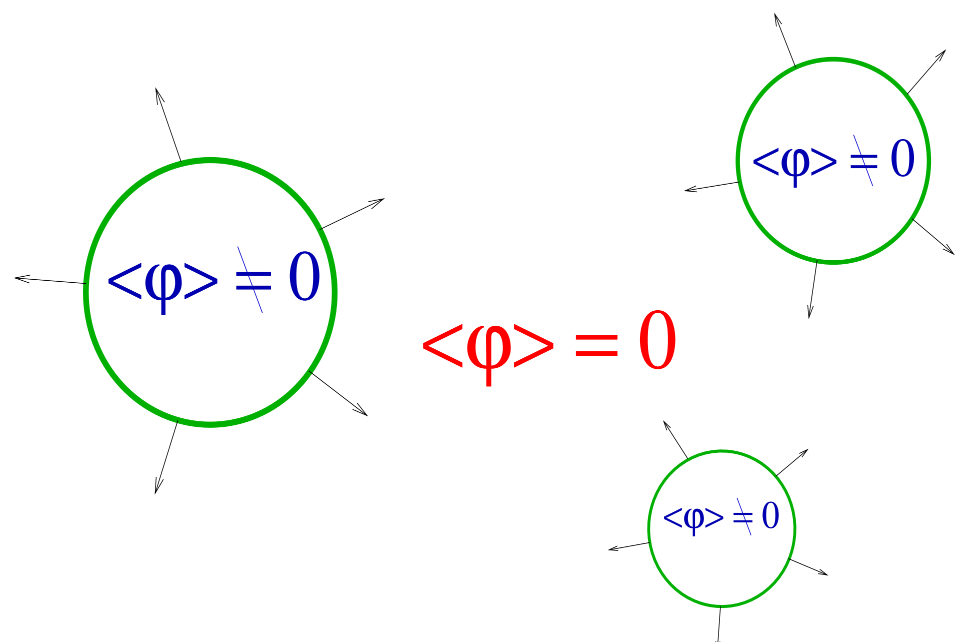


2. Bubble Nucleation

- First order phase transition:



- Bubbles of broken phase are nucleated at $T < T_c$.

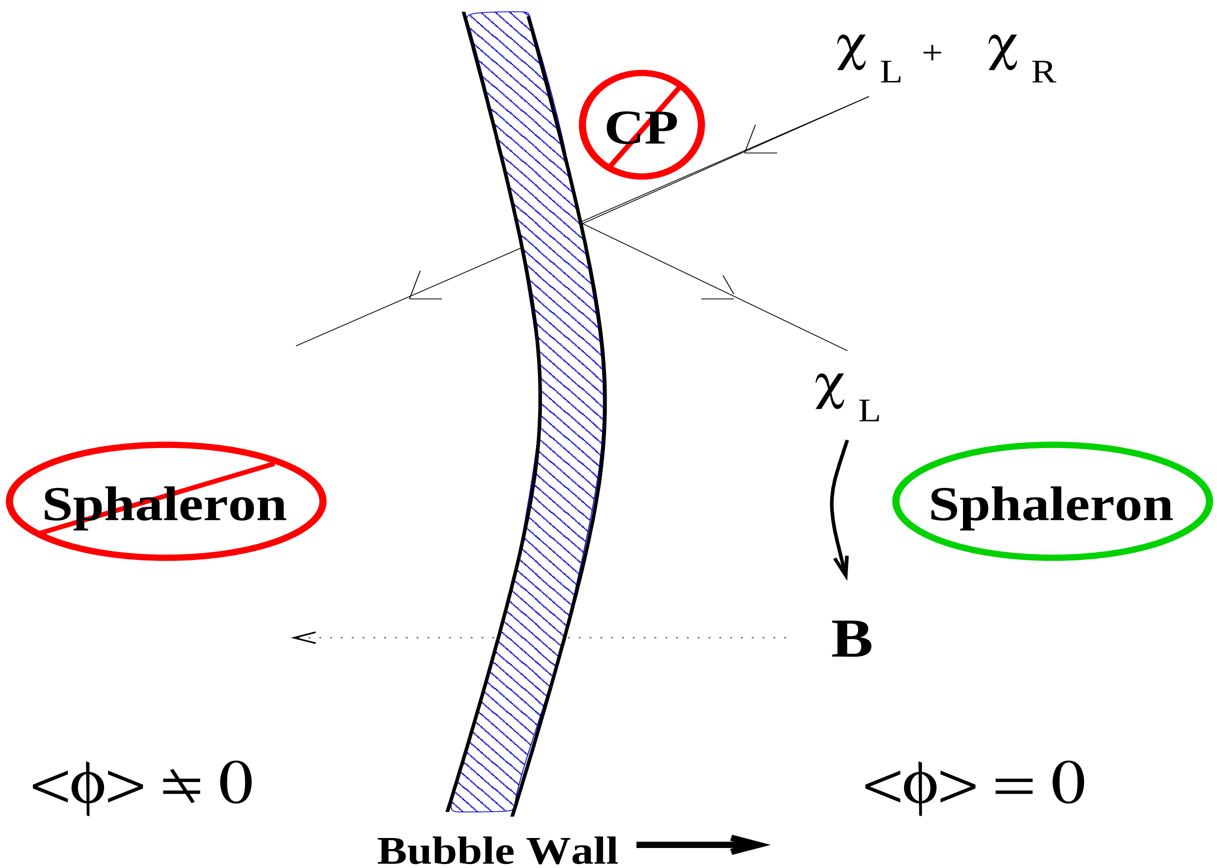


3. Producing Baryons

- CP violation occurs in the bubble wall.

- Sphaleron transitions create baryons outside the bubbles.

- These baryons are swept up into the bubbles.



Aside: Sphalerons

- $B + L$ is $SU(2)_L$ anomalous in the SM (and MSSM).

- Transitions between topologically distinct $SU(2)_L$ vacua:

  $\Delta B = \Delta L = n_g = \#\ generations$. ['t Hooft '76]

- $T = 0 \Rightarrow$ tunnelling (instantons).

$$\Gamma_{inst} \propto e^{-16\pi^2/g_2^2} \simeq 10^{-320}$$

- $T \neq 0 \Rightarrow$ thermal fluctuations (sphalerons). [Klinkhamer+Manton '84]

$$\Gamma_{sp} \sim \begin{cases} T^4\, e^{-4\pi\langle\phi\rangle/g\,T} & \langle\phi\rangle \neq 0 \quad \text{[Arnold+McLerran '87]} \\ \kappa\,\alpha_w^4\,T^4 & \langle\phi\rangle = 0 \quad \text{[Bodeker,Moore,Rummukainen '99].} \end{cases}$$

EWBG in the Standard Model

It doesn't work for two reasons:

1. The electroweak phase transition is first-order only if the Higgs boson is very light, [Kajantie *et al.* '98]

$$m_h \lesssim 70\,\text{GeV}.$$

   LEP II experimental mass bound:

$$m_h > 114.4\,\text{GeV} \qquad (95\%\,c.l.).$$

2. There isn't enough CP violation in the SM. [Gavela *et al.* '94]

EWBG in the MSSM

- SM Problem #1: No First-Order Phase Transition
  - MSSM superpartners modify the Higgs potential.

- SM Problem #2: Not Enough CP Violation
  - Soft SUSY breaking (and μ) introduces new CPV phases:

$$Arg(\mu\, M_a),\; Arg(\mu\, A_i), \ldots$$

- EWBG can work in the MSSM!

- These requirements fix much of the MSSM spectrum.

Requirement #1: A Strong First-Order EWPT

- $V_{eff} = (-\mu^2 + \alpha T^2)\phi^2 - \gamma T\phi^3 + \frac{\lambda}{4}\phi^4 + \dots$

- Quantitative Condition: [Shaposhnikov '88]

$$\frac{\langle \phi(T_c) \rangle}{T_c} \simeq \frac{\gamma}{\lambda} > 1.$$

- $\gamma \neq 0$ is generated by *bosonic* loops.

- The dominant MSSM contribution comes from a light mostly right-handed stop. [Carena,Quirós,Wagner '95]

- $m_h \simeq \sqrt{\lambda}\, v$

$$V_{eff} = (-\mu^2 + \alpha T^2)\phi^2 - \gamma T \phi^3 + \frac{\lambda}{4}\phi^4 + \ldots$$

$$\mathcal{M}_{\tilde{t}}^2 = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_{U_3}^2 + m_t^2 + D_R \end{pmatrix}$$

- MSSM "cubic term":

$$\gamma T \phi^3 \simeq \frac{T}{4\pi}\left[m_{\tilde{t}_1}^2(\phi, T)\right]^{3/2}$$

where

$$m_{\tilde{t}_1}^2(\phi, T) \simeq y_t^2 \phi^2 \left(1 - \frac{|X_t|^2}{m_{Q_3}^2}\right) + \underbrace{m_{U_3}^2 + \xi T^2}_{\delta m^2}.$$

- $\delta m^2 \to 0$, $|X_t| \ll m_{Q_3}$ maximizes the "cubic term".

Implications

- A light right-handed stop:

$$-(100\,\text{GeV})^2 \lesssim m_{U_3}^2 \lesssim 0, \qquad |X_t|/m_{Q_3} \lesssim 0.5$$

$$\Rightarrow 120\,\text{GeV} \lesssim m_{\tilde{t}_1} \lesssim 170\,\text{GeV} \leq m_t.$$

- A heavy left-handed stop:

$$m_{Q_3} \gtrsim 2\,\text{TeV}.$$

- A light SM-like Higgs:

$$M_a \gtrsim 200\,\text{GeV}, \qquad 5 < \tan\beta < 10.$$

$$\Rightarrow m_{higgs} \lesssim 120\,\text{GeV}.$$

Requirement #2: New CP Violation

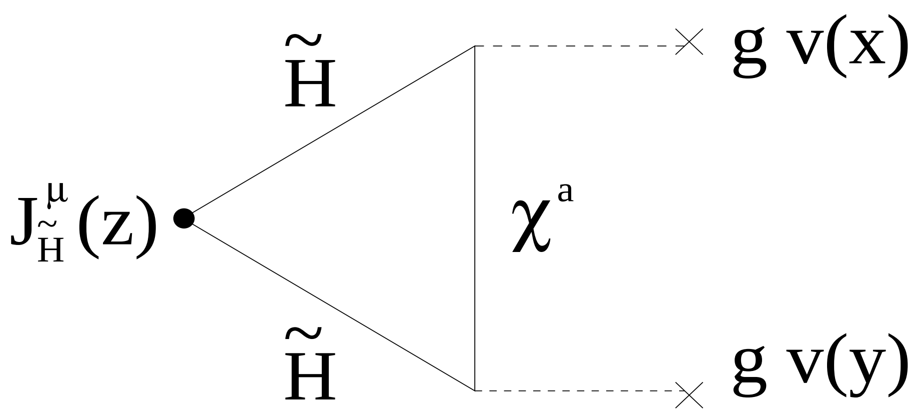
- Main source: Higgsinos.

  e.g.

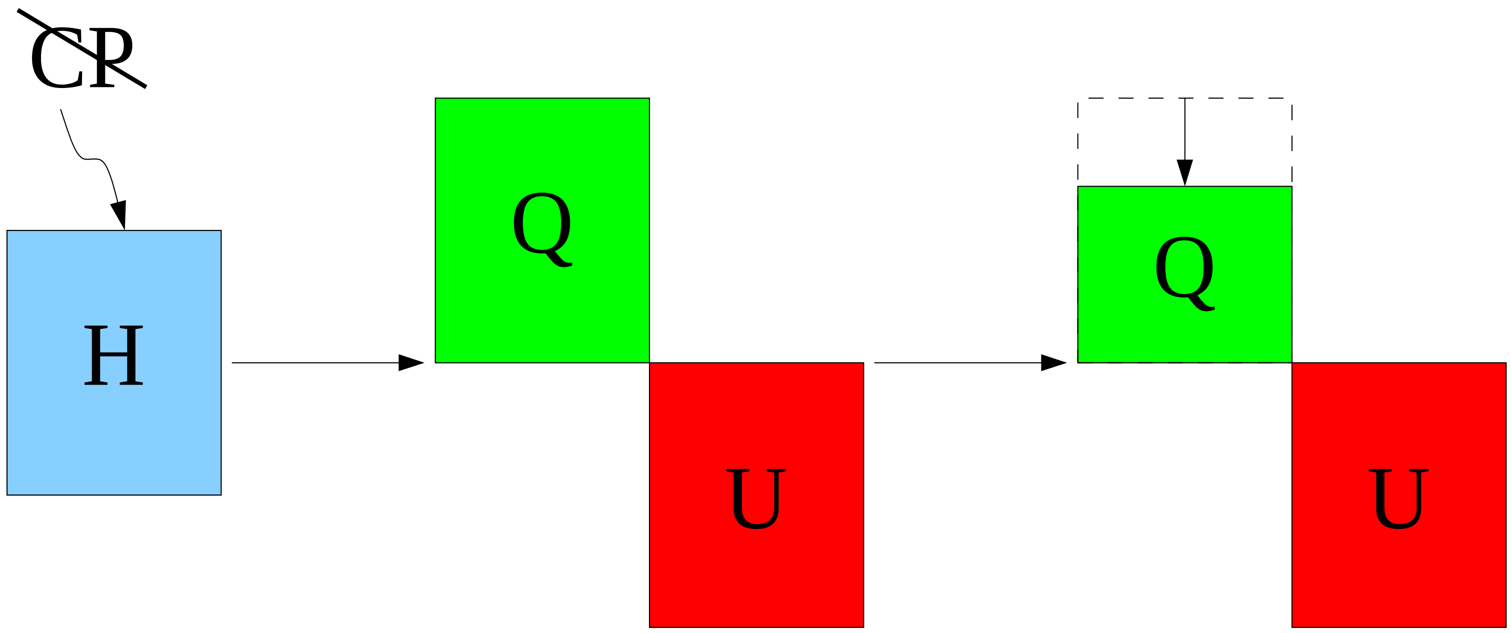
$$\mathcal{M}_{\tilde{\chi}^\pm} \sim \begin{pmatrix} |M_2| & g_2\, v_u(z) \\ g_2\, v_d(z) & e^{i\phi}\,|\mu| \end{pmatrix}, \quad \text{with } \phi = Arg(\mu\, M_2).$$

- CPV source:

$$\left\langle J^0_{\tilde{H}}(z) \right\rangle = \left\langle \bar{\tilde{H}} \gamma^0 \tilde{H} \right\rangle \propto Im(\mu\, M_2)\, \partial_z f(v_u(z),\, v_d(z))$$



- B formation cartoon:



$y_t\, QH_uU^c$ $\qquad$ $SU(2)_L$ sphaleron

- $\mathcal{O}_{sphal} \propto \Pi_i(Q_iQ_iQ_iL_i)$ is sourced by the Q asymmetry.

Implications

- This is enough to generate the baryon asymmetry if:

  [Carena,Quirós,Seco,Wagner '02; Lee,Cirigliano,Ramsey-Musolf '04]

$$Arg(\mu M_{1,2}) \gtrsim 10^{-2}$$

$$\mu,\ M_{1,2} \lesssim 400\,\mathrm{GeV}$$

- New CP violation $\longrightarrow$ electric dipole moments (EDM)

- Strict constraints:

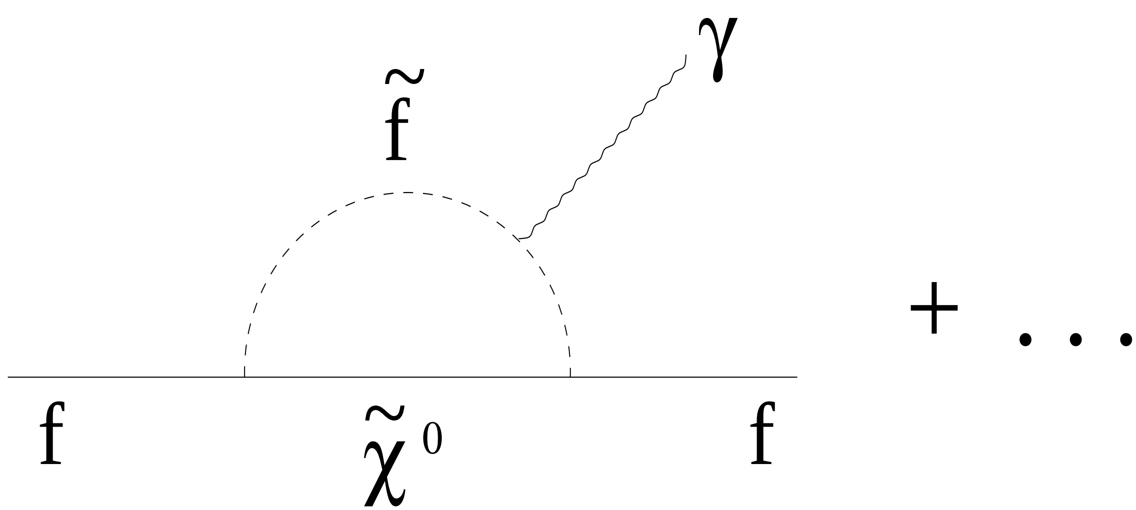
$$|d_e| < 1.6 \times 10^{-27}\ \mathrm{e\ cm}$$ [Regan *et al* '02]

$$|d_n| < 2.9 \times 10^{-26}\ \mathrm{e\ cm}$$ [Baker *et al* '06]

$$|d_{Hg}| < 2.1 \times 10^{-28}\ \mathrm{e\ cm}$$ [Romalis *et al* '01]

- *e.g.* Electron EDM d_e

  One-loop contribution: [Ibrahim+Nath '98]



- Consistency with EWBG and EDM constraints requires

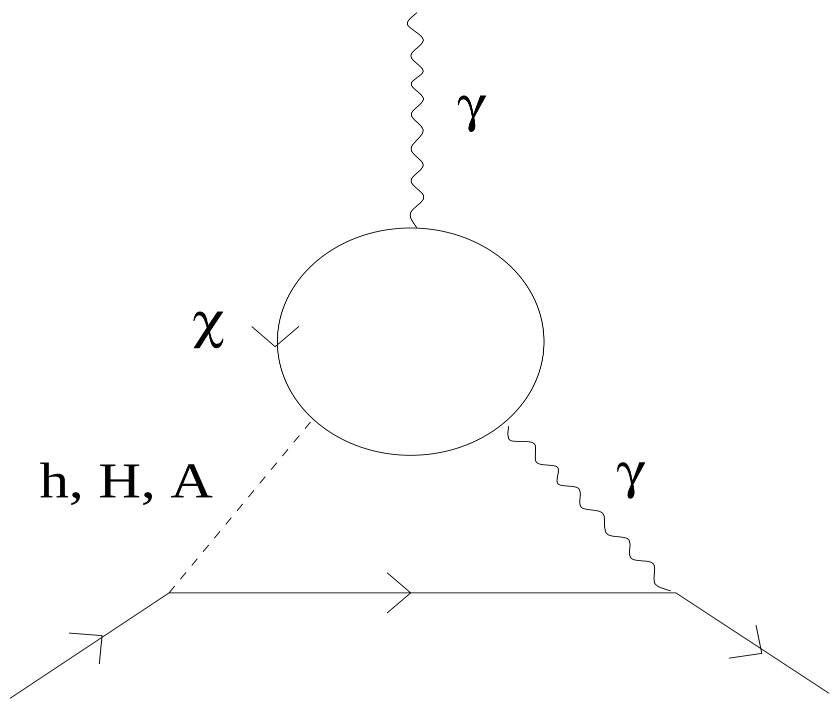
$$m_{\tilde{f}_{1,2}} \gtrsim 5\!-\!10\,\text{TeV}.$$

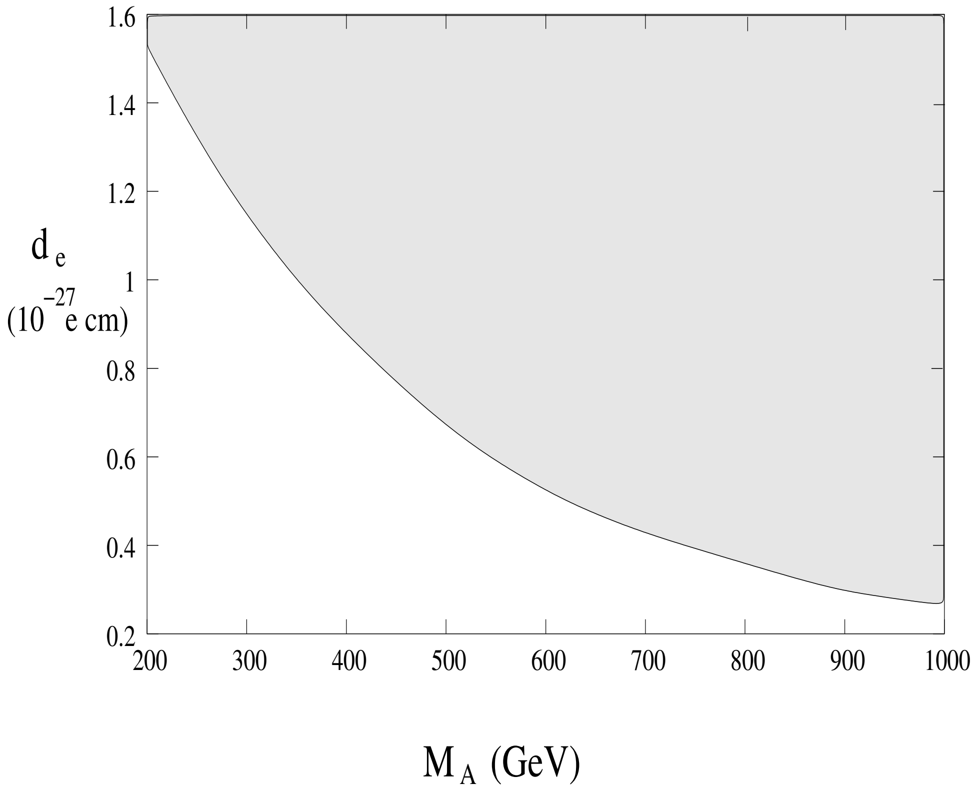
$\Rightarrow$ decouple first and second generation sfermions.

- *e.g.* Electron EDM d_e (contd. . .)

Irreducible two-loop contribution ($\propto Im(\mu\, M_2)$):

[Chang, Chang, Keung '02; Pilaftsis '02]





Upcoming experiments will probe the EWBG region.

[Balázs,Carena,Menon,DM,Wagner '04, Lee,Cirigliano,Ramsey-Musolf '04]

Spectrum Summary

- Light mostly right-handed stop: $m_{\tilde{t}_1} < m_t$.

- Heavy mostly left-handed stop: $m_{\tilde{t}_2} > 2\,\mathrm{TeV}$.

- Light SM-like Higgs boson: $m_h \lesssim 120\,\mathrm{GeV}$.

- Very heavy 1st and 2nd gen. sfermions: $m_{\tilde{f}_{1,2}} \gtrsim 5\,\mathrm{TeV}$.

- Light charginos and neutralinos: $M_{1,2},\ \mu \lesssim 400\,\mathrm{GeV}$.

(Stop Split Supersymmetry?)

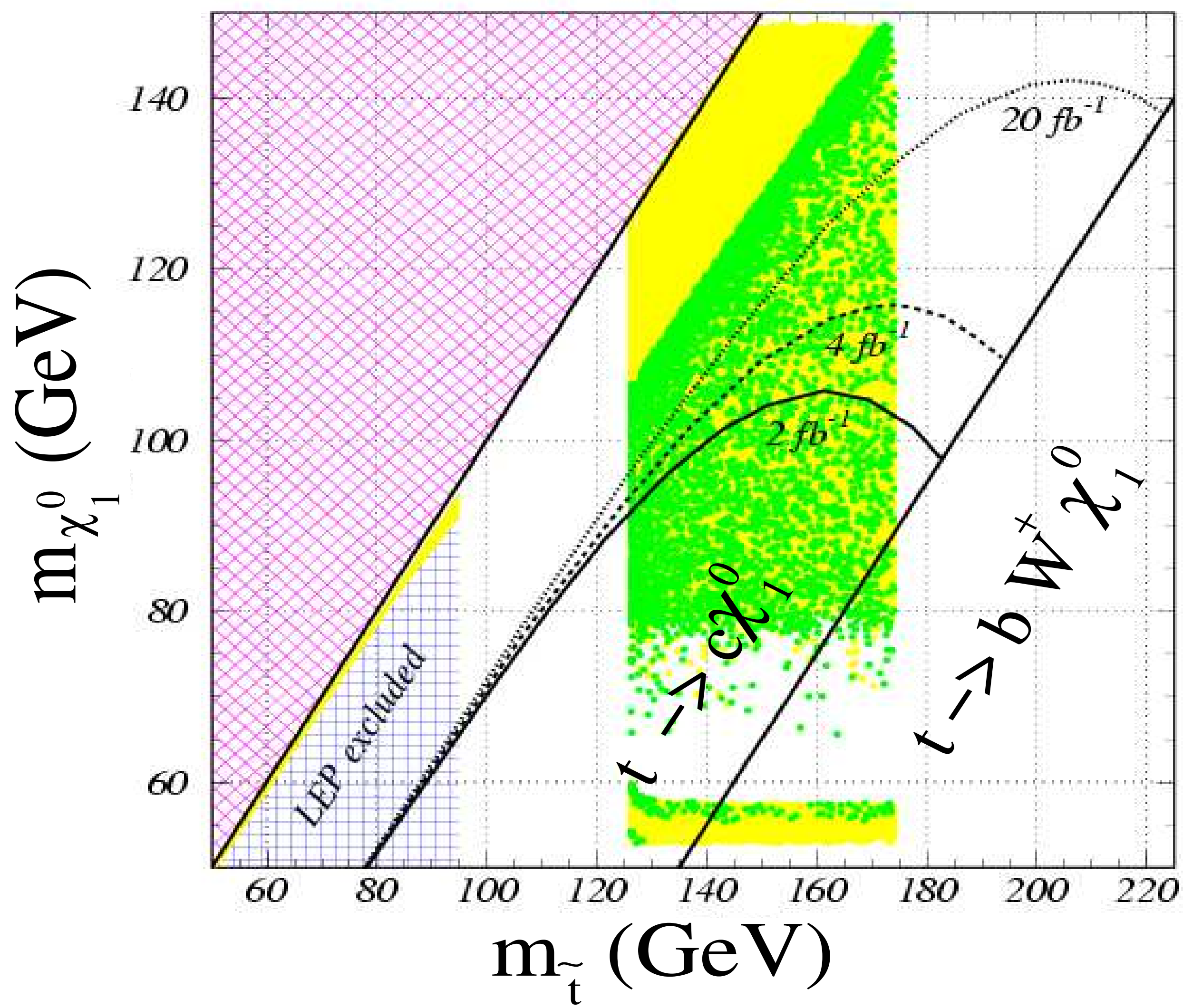
[Carena,Nardini,Wagner '08]

MSSM EWBG at the LHC

MSSM EWBG at the Tevatron?

- A visible light stop since $m_{\tilde{t}_1} < m_t$?

  [Balázs,Carena,Wagner '04]



A Light Stop at the Tevatron?

- Why hasn't the Tevatron seen a light stop with $m_{\tilde{t}_1} < m_t$?

- Not if the light stop is close in mass to the LSP:

$$(m_{\tilde{t}_1} - m_{LSP}) \lesssim 30\,\mathrm{GeV}$$

$\Rightarrow$ decay products are soft and difficult to find.

- Dark Matter Motivation: [Balázs, Carena, Menon, Morrissey, Wagner '05]
  - Bino LSP $\Rightarrow$ too much dark matter.
  - Coannihilation with a light stop reduces the DM density.
  - Requires $(m_{\tilde{t}_1} - m_{LSP}) \lesssim 30\,\mathrm{GeV}$.

Light Stop Direct Searches at the LHC

- $\tilde{t}_1$ are produced copiously but are hard to see.

- Stop Decay Modes:

  - $\tilde{t}_1 \to c\,\chi_1^0 \qquad (\chi_1^0 = LSP)$

    Requires flavor violation.

    $(m_{\tilde{t}_1} - m_{\chi_1^0}) < 30\,\text{GeV} \Rightarrow$ soft charm

    [Balázs,Carena,Wagner '04]

  - $\tilde{t}_1 \to b\,W^{(*)}\,\chi_1^0, \quad \tilde{t}_1 \to b\,\chi_1^{+(*)}$

    Often kinematically impossible, soft decay products.

    [Demina, Lykken, Matchev, Nomerotski '99]

    Can dominate with MFV. [Hiller+Nir '08]

LHC Stop Probe #1: Same Sign Stops
($\tilde{t}_1 \to c\chi_1^0$)

[Kraml+Raklev '05,'06]

- $\tilde{g}\,\tilde{g} \to t\,t\,\tilde{t}_1^*\,\tilde{t}_1^* \to b\,b\,\ell^+\ell^+ + (jets) + \not{E}_T$

  $\Rightarrow$ same sign tops $\to$ same-sign leptons

- Discovery of light stops with 30 fb^{-1} for $m_{\tilde{g}} < 1000\,$GeV.

- Parameter determination is difficult, no c-tags.

- Better prospects with $\tilde{t}_1 \to \bar{b}W^{*+}\chi_1^0$?

LHC Stop Probe #2: Stoponium

[Drees+Nojiri '97; Martin '08]

- $\eta_{\tilde{t}_1} = \tilde{t}_1^* \, \tilde{t}_1^*$ bound state.

- $\underbrace{\Gamma_{\tilde{t}_1 \to c\chi_1^0}}_{\sim \text{eV}} \ll \underbrace{\eta_{\tilde{t}_1} \text{ binding energy}}_{\sim \text{GeV}}$.

- $\eta_{\tilde{t}_1} \to \gamma\gamma$ may be observable at the LHC

  with $< 100\, fb^{-1}$ for $m_{\eta_{\tilde{t}_1}} < 250\,\text{GeV}$. [Martin '08]

- Very good *absolute* mass measurement of $\tilde{t}_1$!

LHC Stop Probe #3: Indirect Higgs Signals

[in progress with Arjun Menon]

- A light stop can modify Higgs production and decay.

  [Kane,Kribs,Martin,Wells '95; Dawson,Djouadi,Spira '96;Djouadi '98;Dermisek+Low '07

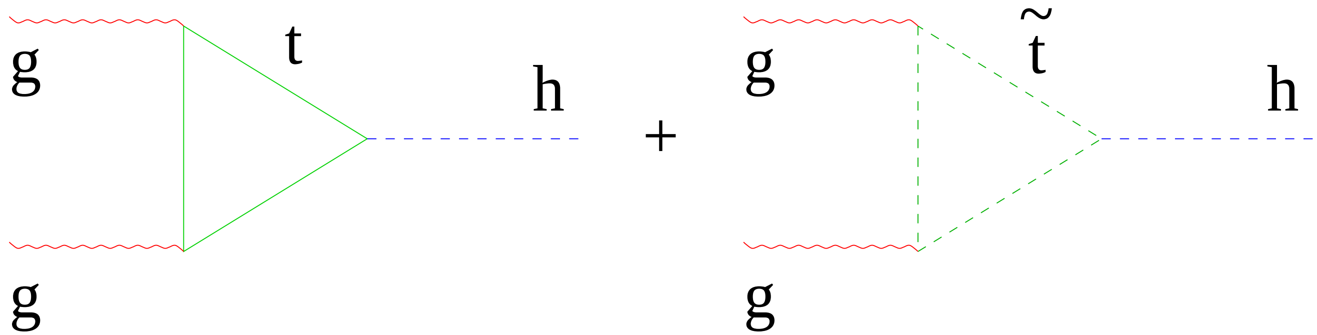
- Effective (EWBG) $h\,\tilde{t}_1\,\tilde{t}_1^*$ coupling:

$$g_{h\tilde{t}_1\,\tilde{t}_1} \simeq m_t^2\left(1-\frac{|X_t|^2}{m_{Q_3}^2}\right).$$

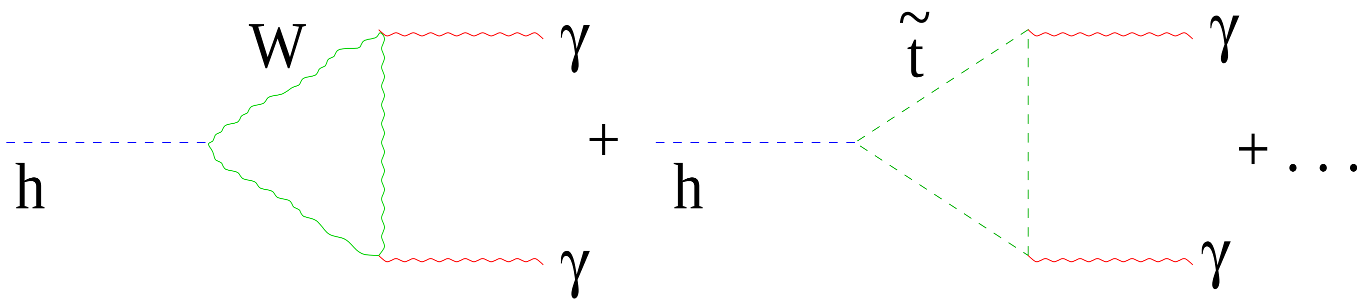
$\Rightarrow$ same combination as in the EWBG phase transition...

EWBG $\Rightarrow$ $|X_t| \ll m_{Q_3}$

- $\sigma(gg \to h)$ is enhanced.



- $\Gamma(h \to \gamma\gamma)$ is suppressed.



LHC Light SM Higgs ($m_h \lesssim 120\,\text{GeV}$) Searches

[ATLAS TDR '99; CMS TDR '07]

- $(gg \to)\ h \to \gamma\gamma$

  5σ with about 10 fb^{-1}

  $\Delta m_h/m_h < 0.2\%$.

- $VBF \to h \to \tau\tau$

  4.0σ with 30 fb^{-1}, 5.5σ with 60 fb^{-1}

- $VBF \to h \to \gamma\gamma$

  3.1σ with 60 fb^{-1}

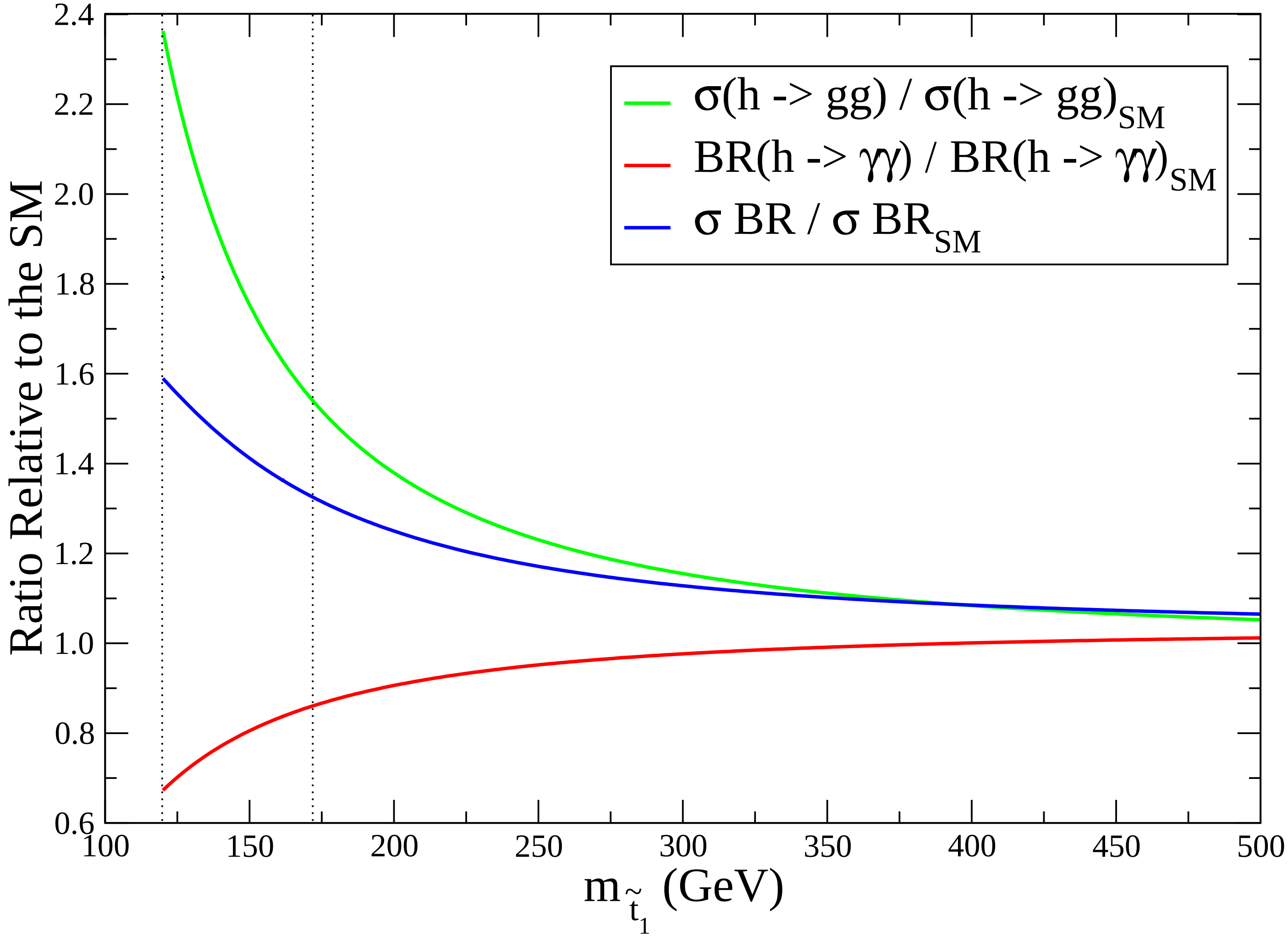
- Wh, $Zh \to \gamma\gamma$

  $4.0\,\sigma$ with 100 fb^{-1} (high $\mathcal{L}$)

- $(gg \to)\ h \to ZZ^*$

  $3.0\,\sigma$ with 30 fb^{-1} ($m_h = 120\,\text{GeV}$)

- $|X_t| \simeq 0$, $\tan\beta = 10$, $M_a =$ large, $m_h = 120\,\mathrm{GeV}$



- $\Delta\sigma/\sigma \lesssim 30\%$, $\Delta BR/BR \lesssim 20\%$, $\Delta\sigma BR/\sigma BR \lesssim 15\%$

[Zeppenfeld '02]

Electroweak-ino Searches

[in progress with Arjun Menon]

- MSSM baryon generation requires $\mu,\, M_{1,2} \lesssim 400\,\mathrm{GeV}$.

  [Carena *et al.* '02,Cirigliano *et al.* '06]

- LHC signatures similar to the focus point scenario?

  [Cirigliano,Profumo,Ramsey-Musolf '06]

- Important difference - light stop in the decay chains:

  [Carena+Freitas '06]

$$\begin{aligned} \chi^{\pm}_{1,2} \;&\to\; \tilde{t}_1\, b \quad \text{(if possible)} \\ \chi^0_{(i>1)} \;&\to\; Z\,\chi^0,\; h\,\chi^0,\; W^{\pm}\,\chi^{\mp} \end{aligned}$$

Summary

- On top of everything else, the MSSM can account for the dark matter and the baryon asymmetry.

- Baryon production $\longrightarrow$ electroweak baryogenesis.

- EWBG requires a light stop, light -inos, heavy scalars.

- This scenario can be challenging at the LHC.

- Higgs boson production and decay gives an indirect probe.

- Connection between colliders and cosmology!?

MSSM EWBG at the LHC

Extra Slides

Sphalerons

- $B + L$ is a symmetry of the classical SM and MSSM Lagrangians.

  This symmetry is broken by quantum effects.

- The only processes that violate $B + L$ are transitions between topologically inequivalent $SU(2)_L$ gauge vacua.

- Each transition produces $\Delta B = \Delta L = n_g = \#generations$.

- At $T = 0$, these transitions proceed by tunnelling (instantons).

$$\Gamma \propto e^{-16\pi^2/g^2} \sim 10^{-160}.$$

- At $T \neq 0$, these can go via thermal fluctuations.

  $\Rightarrow$ sphaleron transitions.

  The transition rate (per unit volume) is [Arnold+McLerran '87]

$$\Gamma_{sp} \sim \begin{cases} T^4\, e^{-4\pi\langle\phi\rangle/g\,T} & \langle\phi\rangle \neq 0 \\ \alpha_w^4\, T^4 & \langle\phi\rangle = 0. \end{cases}$$

- The net rate of B violation due to the sphalerons is

$$\frac{dn_B}{dt} = -\frac{\Gamma_{sp}}{T^3}\left[\mathcal{A}\sum_{i=1}^{n_g}(3\,n_{q_L^i} + n_{l_L^i}) + \mathcal{B}\,n_B\right],$$

for positive dimensionless constants $\mathcal{A}$ and $\mathcal{B}$.

- The first term corresponds to the chiral fermion charge:

  e.g. n_{q_L} = (# left-handed quarks) - (# right-handed antiquarks).

- In the absence of this asymmetry, baryon number relaxes to zero as

$$n_B(t) = n_B(0)\,e^{-\mathcal{B}\,(\Gamma_{sp}/T^3)\,t}.$$

- When non-zero, the chiral charge acts as a source for baryon production.

Beyond the MSSM

Why?

The minimal SUSY SM faces a few difficulties:

- The tree-level mass of the lightest CP-even Higgs is bounded by M_Z:

  $$m_h^2 \leq M_Z^2 \cos^2 2\beta,$$

  but LEP II finds $m_h \gtrsim 114$ GeV.

- On the other hand, a strongly first-order electroweak phase transition, needed for EWBG, is only obtained for

  $$m_h \lesssim 120 \text{ GeV}.$$

- μ problem:

  The dimensionful superpotential coupling $\mu\, H_1 \cdot H_2$, with $\mu \sim \mathcal{O}(\text{TeV})$, is needed to break the electroweak symmetry.

  Why is $\mu \ll M_{GUT}$ or M_{Pl}?

  (However, see [Giudice+Masiero '88].)

Adding a gauge singlet S helps:

- $\mu\, H_1 \cdot H_2 \to \lambda\, S\, H_1 \cdot H_2$ solves the μ problem;

  S gets a VEV at a scale set by the soft terms.

- The upper bound on the lightest CP-even Higgs mass becomes

$$m_h^2 \leq M_Z^2 \left(\cos^2 2\beta + \frac{2\lambda^2}{\bar{g}^2} \sin^2 2\beta \right).$$

- A new $S\, H_1 \cdot H_2$ trilinear soft term makes the electroweak phase transition more strongly first-order.

  [Pietroni '92, Davies *et al* '96, Schmidt+Huber '00, Kang *et al* '04.]

But . . .

- The singlet must be charged under some additional symmetry to forbid new dimensionful ($d < 4$) couplings.

- The most popular choice is a $\mathbb{Z}_3$ symmetry, which yields the superpotential

$$W = \lambda\, S\, H_1 \cdot H_2 + \kappa\, S^3 + (\text{MSSM terms}).$$

  This model is called the NMSSM,
  the Next-to-Minimal Supersymmetric Standard Model.

- When S gets a VEV, the $\mathbb{Z}_3$ symmetry is broken producing cosmologically unacceptable domain walls.

- The domain wall problem can be avoided by including non-renormalizable operators that break $\mathbb{Z}_3$. However, these generate a large singlet VEV which destabilizes the hierarchy.
  [Abel,Sarkar,+White '95]

A way out: the nMSSM

- Both problems can be avoided by imposing discrete R-symmetries on both the superpotential and the Kähler potential.
  [Pangiotakopoulos+Tamvakis '98/'99, Pangiotakopoulos+Pilaftsis '00, Dedes *et al* '00]

- The resulting model is the nMSSM, the not-quite MSSM.
  - Superpotential:
  $$W = \frac{m_{12}^2}{\lambda^2} S + \lambda S H_1 \cdot H_2 + \text{(MSSM matter terms)},$$
  - Soft-breaking potential:
  $$\begin{aligned} V_{soft} &= t_s(S + h.c.) + m_s^2 |S|^2 \\ &\quad + a_\lambda (S H_1 \cdot H_2 + h.c.) + \text{(MSSM terms)}. \end{aligned}$$

- The same superpotential and soft-breaking terms also arise in the low-energy limit of the Fat Higgs model.
  [Harnik *et.al.* '03]

EWBG in the nMSSM

- In the SM and MSSM, the effective potential has the form:

$$V_{eff} \simeq (-\mu^2 + \alpha T^2)\phi^2 - \gamma T \phi^3 + \frac{\lambda}{4}\phi^4 + \ldots .$$

  γ drives the transition to be first order.

  $\gamma = 0$ at tree-level in the SM and MSSM.

- SM: the PT isn't strong enough.

- MSSM: one-loop corrections to V_{eff} from a light stop can make the PT strong enough, but only for $m_h \lesssim 120$ GeV.

  [Carena *et al* '96, Laine '96, Losada '97, Laine+Rummukainen '00]

- nMSSM: the trilinear soft term $S\, H_1 \cdot H_2$ contributes to γ at tree level making the PT first-order, even without a light stop, and for $m_h > 120$ GeV.

Charginos, Neutralinos, and Dark Matter

- The chargino mass matrix is identical to the MSSM, but with $\mu \to -\lambda\, v_s$.
- The fermion component of S, the singlino, produces a fifth neutralino state.

$$\mathcal{M}_{\tilde{N}} = \begin{pmatrix} M_1 & \cdot & \cdot & \cdot & \cdot \\ 0 & M_2 & \cdot & \cdot & \cdot \\ -c_\beta s_w M_Z & c_\beta c_w M_Z & 0 & \cdot & \cdot \\ s_\beta s_w M_Z & -s_\beta c_w M_Z & \lambda v_s & 0 & \cdot \\ 0 & 0 & \lambda v_2 & \lambda v_1 & 0 \end{pmatrix}$$

- We relate M_1 to M_2 by universality and allow for a common phase;

$$M_2 = |M_2|\, e^{i\phi} \simeq \frac{\alpha_2}{\alpha_1}\, M_1 .$$

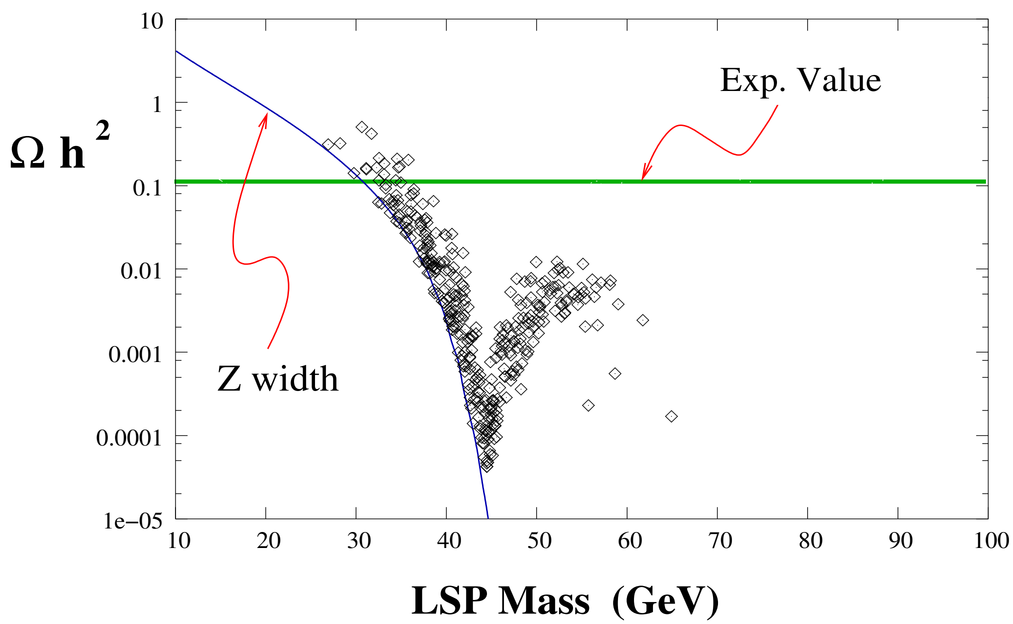
- $\lambda(M_Z) \lesssim 0.8$ for perturbative unification.
- There is always a light neutralino: $m_{\tilde{N}_1} \lesssim 60$ GeV.

e.g. $$m_{\tilde{N}_1} \simeq \frac{2\,\lambda\, v_1\, v_2\, v_s}{v_1^2 + v_2^2 + v_s^2},$$

for M_1, $M_2 \to \infty$, and $\tan\beta \gg 1$ or $v_s \gg v$.

EWBG and DM Results

- Neutralino relic densities consistent with EWBG:



- Dots = parameter sets consistent with EWBG.

- Green line = WMAP result:

$$\Omega_{DM}\,h^2 = 0.113^{+0.016}_{-0.018}.$$

- Blue line = LEP Z-width constraint:

$$\Gamma(Z \to \tilde{N}_1\tilde{N}_1) < 2.0\ \text{MeV}.$$

Higgs Bosons

- Physical states: 3 CP-even, 2 CP-odd, 1 charged.
- For $M_a^2 \to \infty$, the charged state, one CP-even state, and one CP-odd state decouple.
- The remaining CP-odd state is pure singlet with mass

$$m_P^2 = m_s^2 + \lambda^2 v^2.$$

- The remaining CP-even states have mass matrix

$$M_S^2 = \begin{pmatrix} M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta & \cdot \\ v(a_\lambda \sin 2\beta + 2\,\lambda^2 v_s) & m_s^2 + \lambda^2 v^2 \end{pmatrix}.$$

  This is in the basis (S_1, S_2), where S_1 is SM-like, and S_2 is a singlet.

- EWBG $\Rightarrow$ $\sqrt{m_s^2 + \lambda^2 v^2} \lesssim 250$ GeV.
- If so, there are two light CP-even and one light CP-odd Higgs bosons.
- The lightest CP-even and CP-odd states usually decay invisibly into pairs of the neutralino LSP.
- The CP-even states can still be detected at the LHC through vector boson fusion channels. Define

$$\eta = BR(h \to inv)\, \frac{\sigma(VBF)}{\sigma(VBF)_{SM}}.$$

- The luminosity needed for a 5σ discovery is then [Eboli+Zeppenfeld '00]

$$\mathcal{L}_{5\sigma} \simeq 8\text{fb}^{-1}/\eta^2.$$

  - $\eta \simeq 0.5 - 0.9$ for the SM-like state.
  - $\eta \simeq 0.0 - 0.3$ for the mostly singlet state .